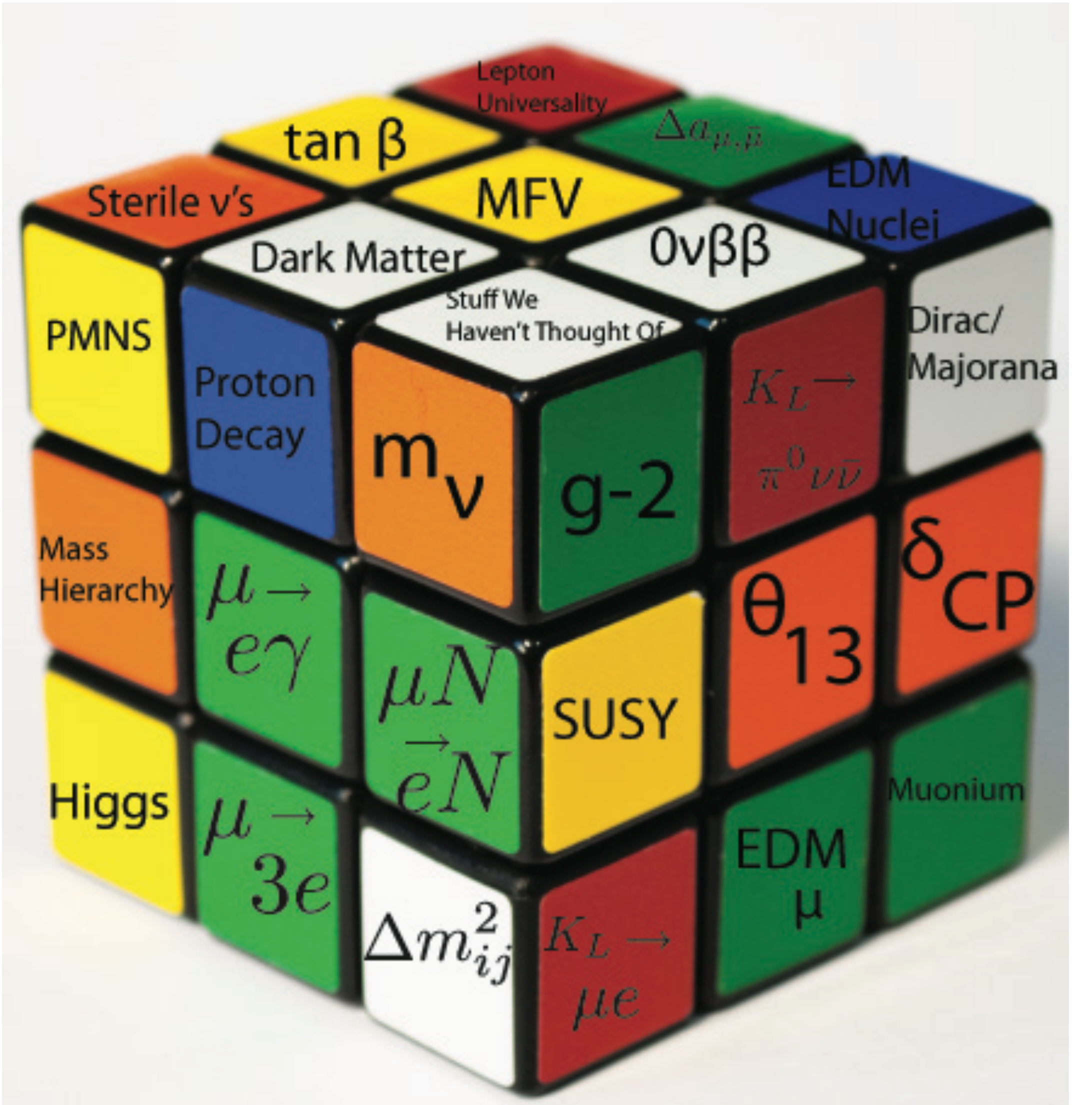
MUON PHYSICS AT PROJECT X

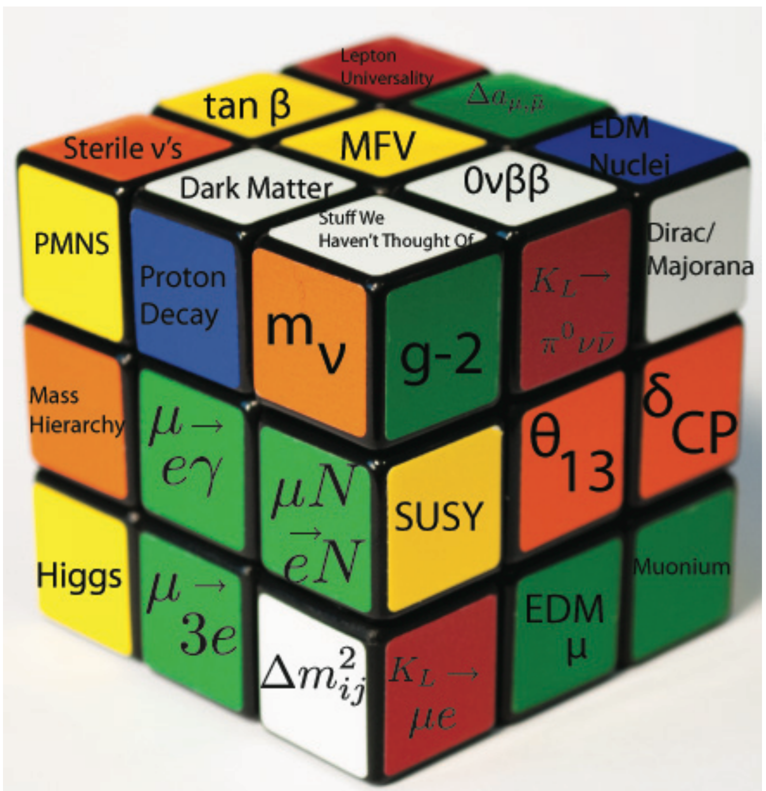
EXPERIMENTAL ISSUES

Purpose of the Study:



- Note this problem is stated on the Lattice
- No Room for Extra Dimensions, sorry

Methods of the Study:



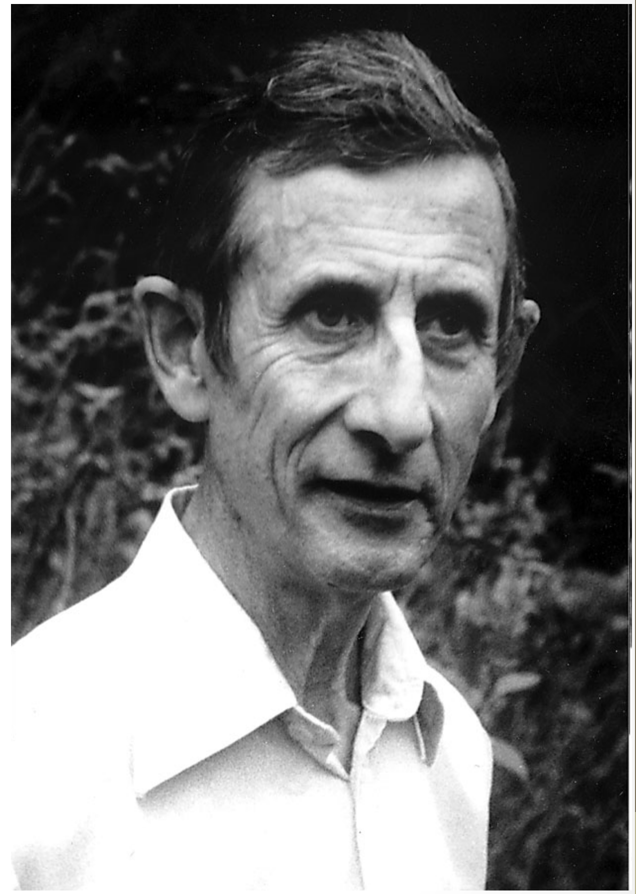
Trackers
Calorimeters
SCRF
Picosecond Timing
Duct Tape

Solution to Extra Dimension Problem

Take That…

"The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier. For making important discoveries, high accuracy was more useful than high energy."

Freeman Dyson, review of *The Lightness of Being*, F. Wilczek



http://www.nybooks.com/articles/archives/2009/apr/09/leaping-into-the-grand-unknown/

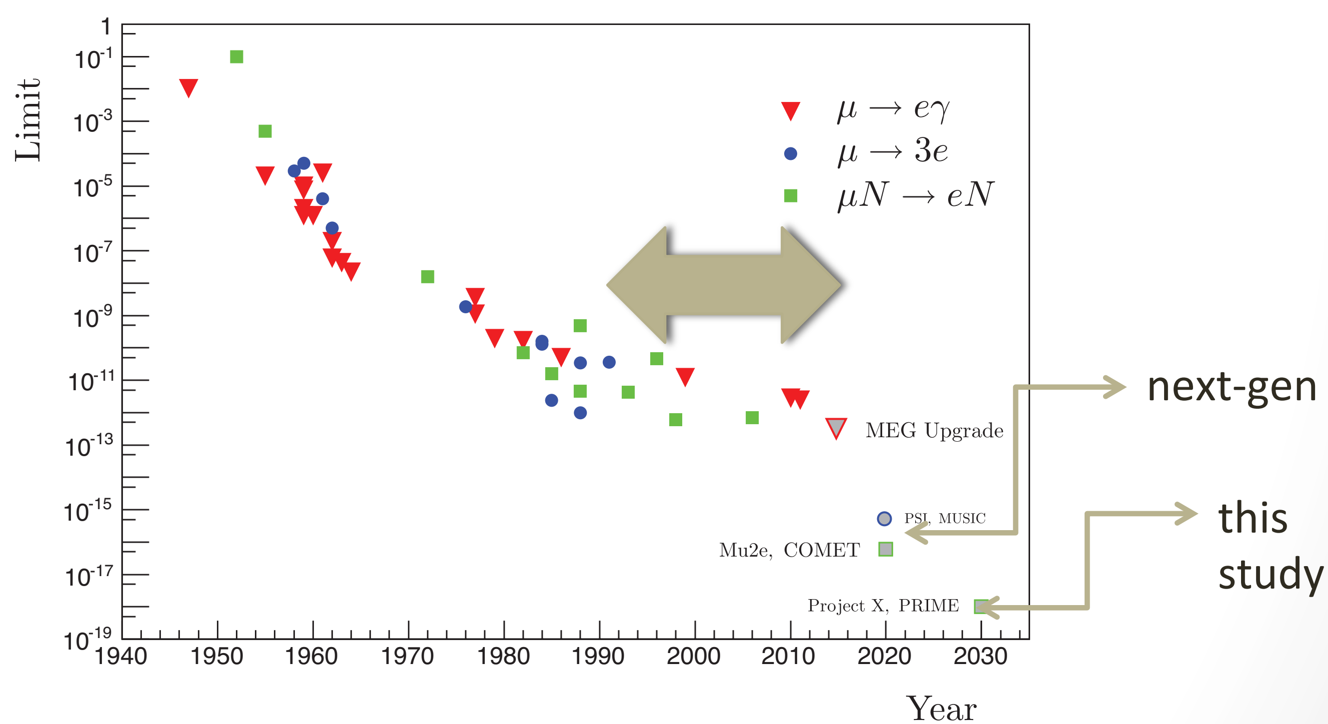
Muons: Experimental Goals

- Define a suite of Experiments
  - What do we want to measure?
    - CLFV and non-CLFV
      - $\mu \rightarrow e\gamma$, 3e, $\mu N \rightarrow eN$ conversion, $\mu^- N \rightarrow e^+ N$ ($\Delta L=2$)
      - Muonium-anti-muonium?
      - g-2
        - Unfairly ignoring upgrades and μ^+ measurements; the case is so obvious I'm skipping it…
      - Proton radius/Lamb shift?
  - How well do we want to measure it? (see Siegrist's talk yesterday!!)
    - "If you can measure something an order of magnitude better, you should do it" – Jim Cronin
    - Most funding agencies and committees are not as smart as Cronin
      - Therefore we need theory guidance on what to try for!
  - Less flippantly, the large value of θ_{13} is telling us something. We know CLFV and neutrino oscillations are connected, and both are connected to kaons and taus and *g-2* and EDMs.

Context: CLFV Experiments

- CLFV in the Muon System improved steadily for many years, then leveled out

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$

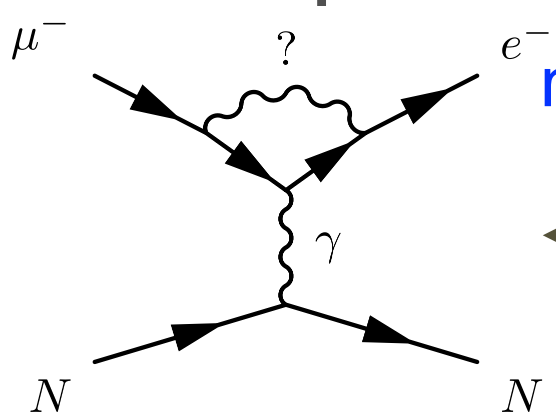


CLFV for Dummies

- Very generically, “loops” and contact-terms

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} \; + \; \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + (\bar{d}_L\gamma_\mu d_L)$$

“Loops”



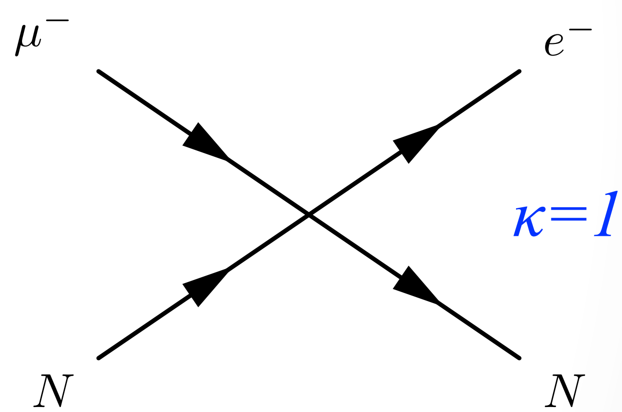
Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

mass scale Λ

κ

“Contact Terms”

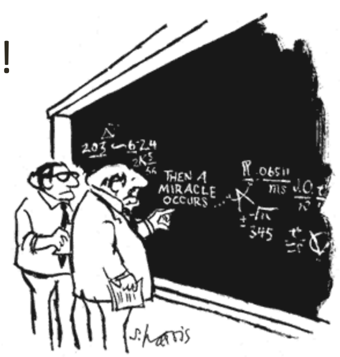


New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Does not produce μ→eγ

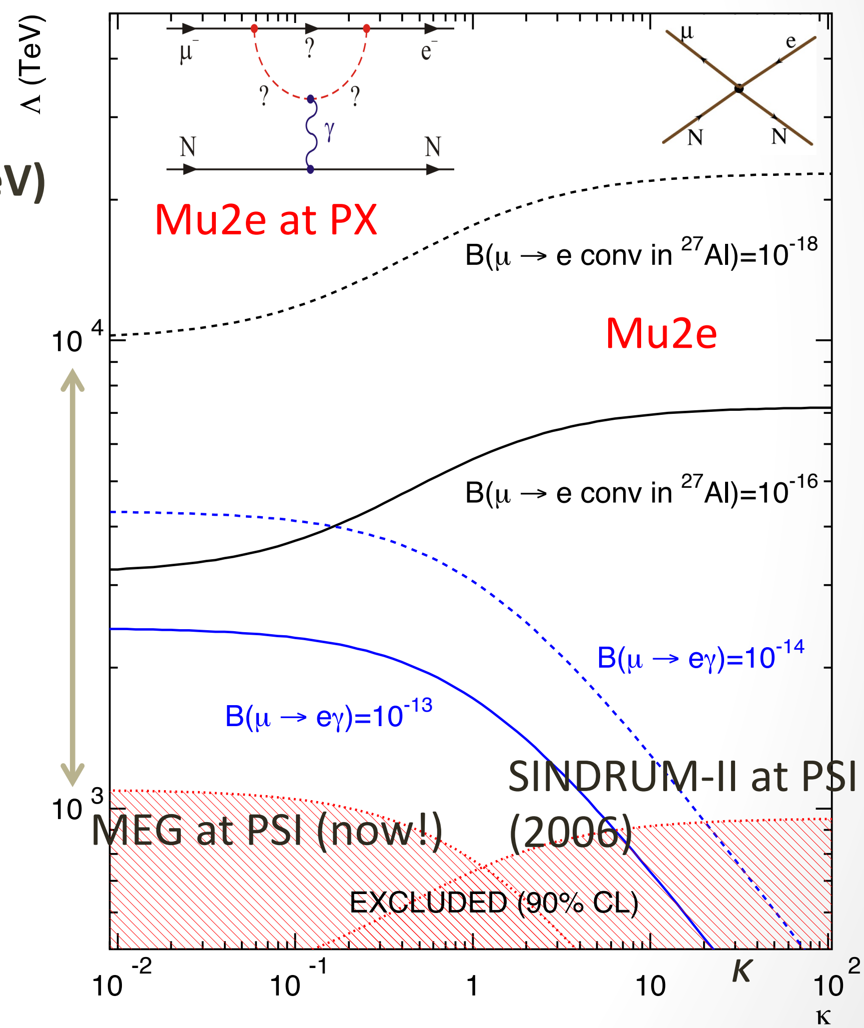
Why Do we Need More than One Experiment?

- Note $\mu \to e\gamma$ and μe (Mu2e)conversion (and $\mu \to 3e$) are complementary
- Suppose:
  - Mu2e/3e, but not $\mu \to e\gamma$
    - Contact! NP at a very high mass scale
  - Both
    - Loop!
  - Neither



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

New version, A. de Gouvea



Mu2e Needs to be done at PX

- If there’s a signal, *must* probe with different nuclei
- But these leads to new demands on muon beam since lifetime of muonic atom becomes short
- PX is flexible

V. Cirigliano et al., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

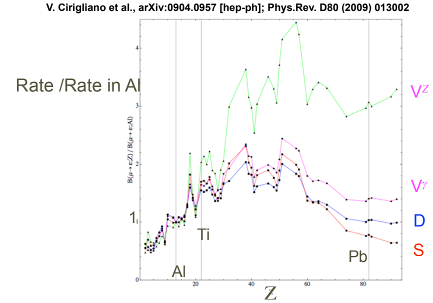
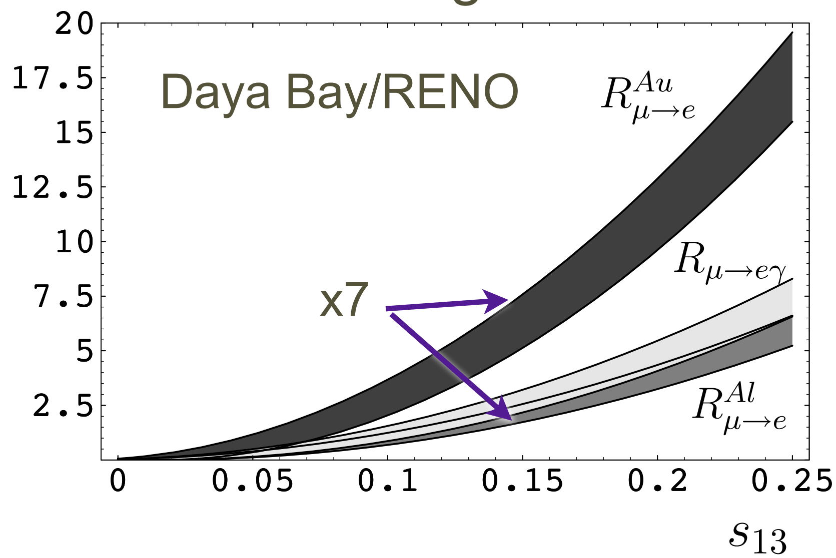


Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

Talks by Polly, Wei, Ankenbrandt, Maloney

can see large effect



s_{13} is now known to be non-zero!

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**.
e-Print: **hep-ph/0507001**

Problems for Experimenters

- *What is the State of the Art and How Can We Advance It?*
  - $\mu \to e\gamma$ (joint session with Calorimeter Group)
    - How much better than MEG is possible at PX?
    - What are the right methods? (Molzon, Calorimetry session)
      - Convert the photon?
        - Better resolution, lower rate
      - Use EM Calorimetry
        - Worse resolution than tracking
  - $\mu \to 3e$
    - PSI LOI: active pixel tracker surrounding a target
      - A novel experiment searching for the lepton flavour violating decay $\mu \to eee$
      - Can it be combined with a $\mu N \to eN$ conversion experiment?
        - $\mu \to 3e$ is μ^+, $\mu N \to eN$ is μ^- but people have suggested it

Zooming In: $\mu N \rightarrow eN$ Questions

- Is the Mu2e tracker/calorimeter pairing optimal?
  - Two trackers? No calorimeter?
    - Calorimeters have worse resolutions on the conversion track than trackers, but have other advantages and are different technology
- Muon Beam Design:
  - Is the Mu2e S or the COMET C workable at PX intensities?
    - Initial beam flash may overwhelm detector. FFAG or HCC?
- What time structures do we want?
- Backgrounds:
  - Are there better ways to measure "out-of-time" beam?
    - Direct measurement of protons is very difficult
- How do we get an absolute calibration? How good does it need to be?
  - Electron accelerator in situ? (talk by Gai from ANL)

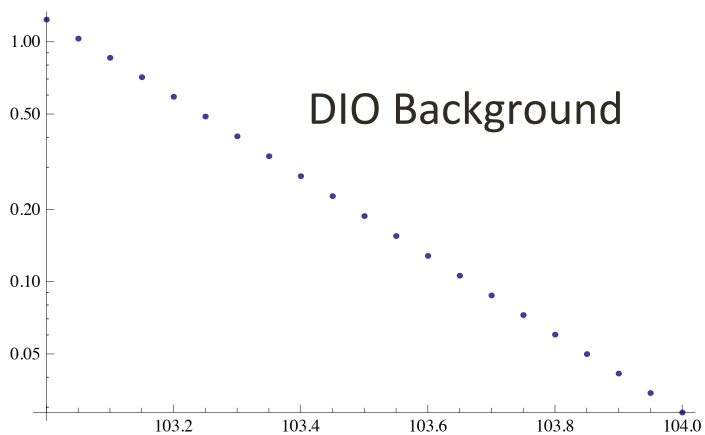
Project X Advantages for Mu2e

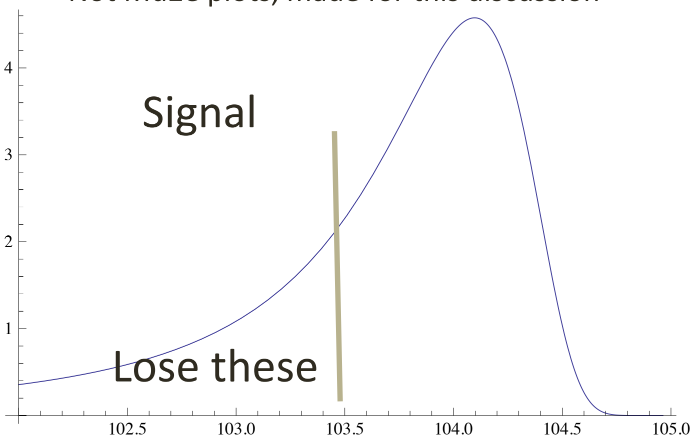
- *Beam Power*:
  - Aside from raw statistics, lets us solve other problems
- *Time Structure*
  - A problem in Mu2e/Booster Era is radiative pion capture
  - Too detailed for this talk, but "wait" for pions to decay
  - Beam at Mu2e is 200 nsec wide and that yields background since you can't wait forever!
  - PX can give O(10 nsec) beam widths, a huge improvement!
- *Lower Energy*
  - Another problem in Mu2e/Booster is antiproton production
    - Antiprotons wander down beamline (same charge as μ^-), annhihilate, and make pions -> radiative pion capture
    - We're on a threshold for pbars, so slightly lower energy yields huge reduction
- *Can tradeoff the above to optimize sensitivity*

Calibration Issues in Mu2e

- Have a rapidly falling background from muon decay-in-orbit, ~ $(E_{conv} - E)^5$ near endpoint (this plot includes smearing and some other effects)

Not Mu2e plots, made for this discussion



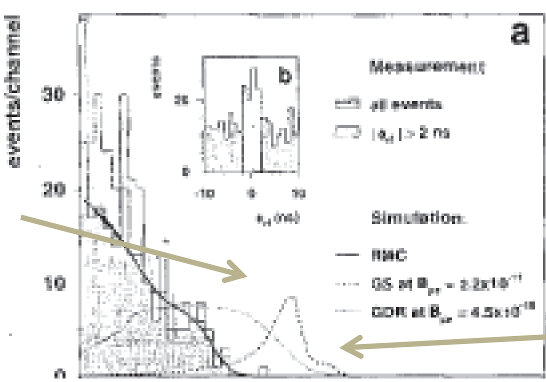


- "Typical" signal cut at 103.5 -> ~0.2 bkg events
- Uncertainty in Calibration of 0.1% (mu2e) at 1σ is an error of ~0.15 event at 90%CL.
- If x10-100 more sensitive search, this becomes a problem!
  - Mu2e plans to use monochromatic $\pi^+ \to e\upsilon$ electron at 69.8 MeV/c
    - Need to change field scale from 105 to 69.8, running conditions-> not optimum

$\Delta L=2: \quad \mu^- N(A,Z) \rightarrow e^+ N(A,Z-2)$

- Ferociously difficult for two reasons:
  - Final state nucleus is in a different state from initial state nucleus, therefore no coherent enhancement as in mu-e conversion
  - Final state can be either ground or excited state. Excited state is usually taken to be GDR with a width of 20 MeV, *huge* on these scales. At least GDRs are well-known.
  - These leave us open to backgrounds from radiative muon capture and other nasty, hard-to-calculate processes.
  - But even just using GS in interesting

GDR

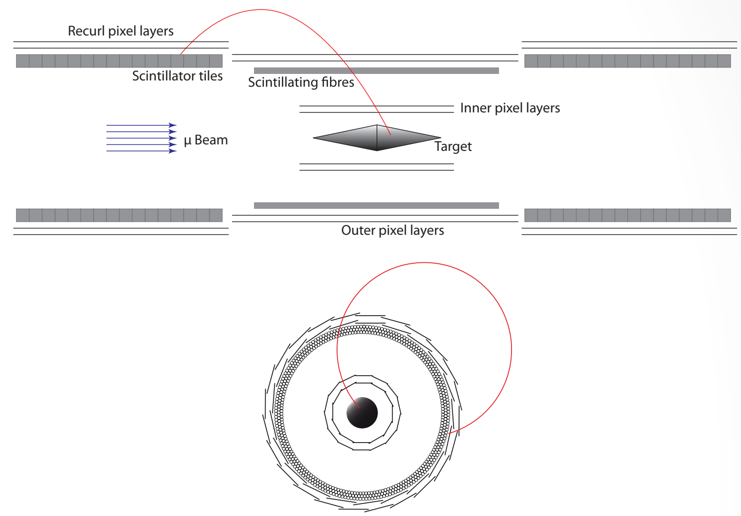


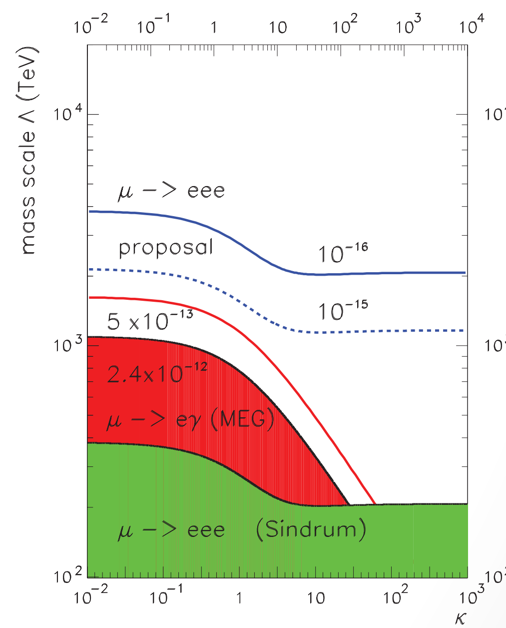
GS

SINDRUM-II
best measurement:
Kaulard, J., et al. (1998),
Physics Letters B 422 (1-4), 334
$< 1.7\text{e-}12$ to GS
$< 3.6\text{e-}11$ to GDR
Fair to say "GDR" state never understood

$\mu^+ \to 3e$ at PSI: 10^{-15} to 10^{-16}

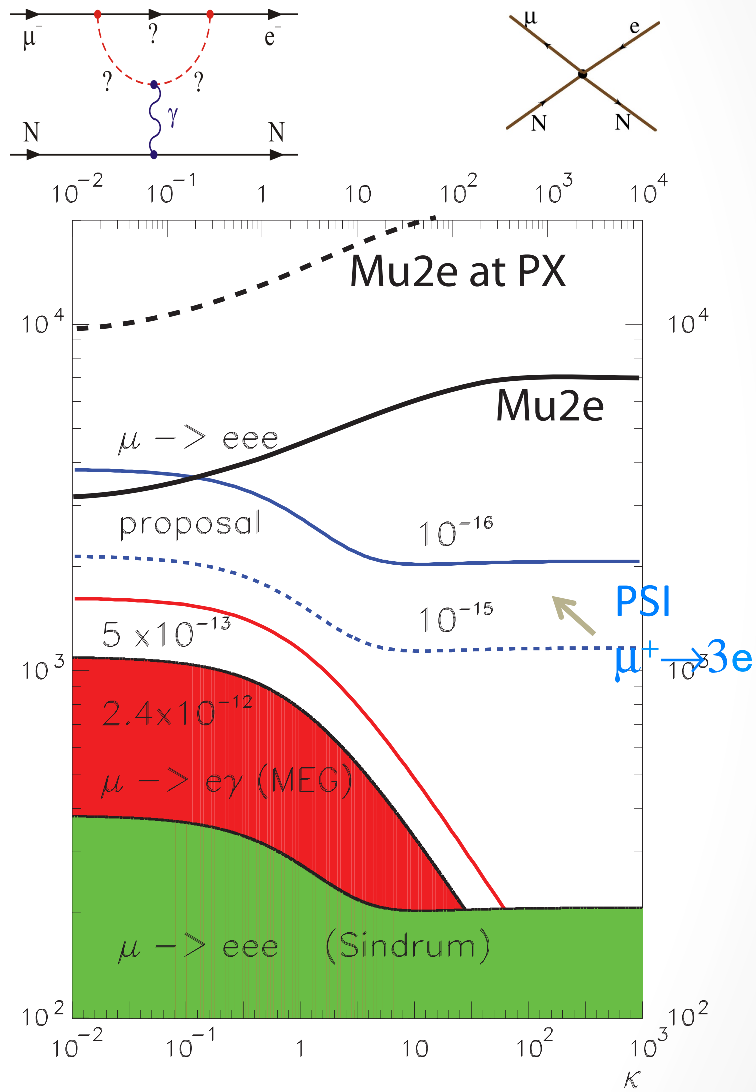
- Current <1.0e-12 at 90% CL: Bellgardt et al., Nuclear Physics B 299 (1998)
- LOI to PSI:
  - Stopped μ^+ beam with SciFi and Pixels
- $\mu^+ \to 3e$ shares much with $\mu^+ \to e\gamma$:
  - Accidentals and Resolution
    - Here, from $\mu^+ \to 3e\nu\bar{\nu}$ at BR= (3.4e−05) overlapping other decays
    - Bhabha scattering of positrons from regular Michel decay can yield a pair in combination with another decay
- Need high resolution tracker
  - Innovative pixel tracker
  - LOI at PSI: A novel experiment searching for the lepton flavour violating decay μ → eee



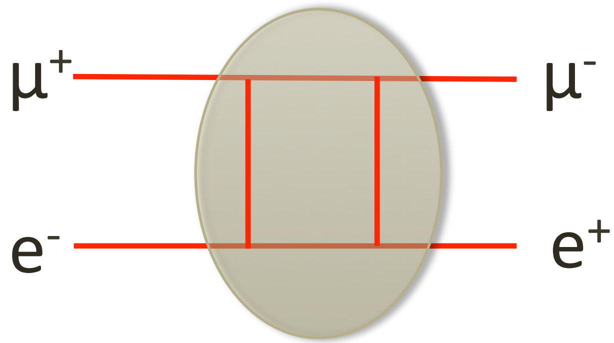


CLFV in Muons: Current and Planned

- Compare everyone on same plot
- $\mu^+ \to 3e$ and Mu2e are a terrific complement
- Added to MEG has enormous discriminating power
- The combination pins down the mass scale and relative contribution of loops and contact terms
- *HAVE TO DO ALL THREE AS WELL AS POSSIBLE*



Muonium



V-A new physics: coupling

$$G_{\mathrm{Mu}\,\overline{\mathrm{Mu}}}$$

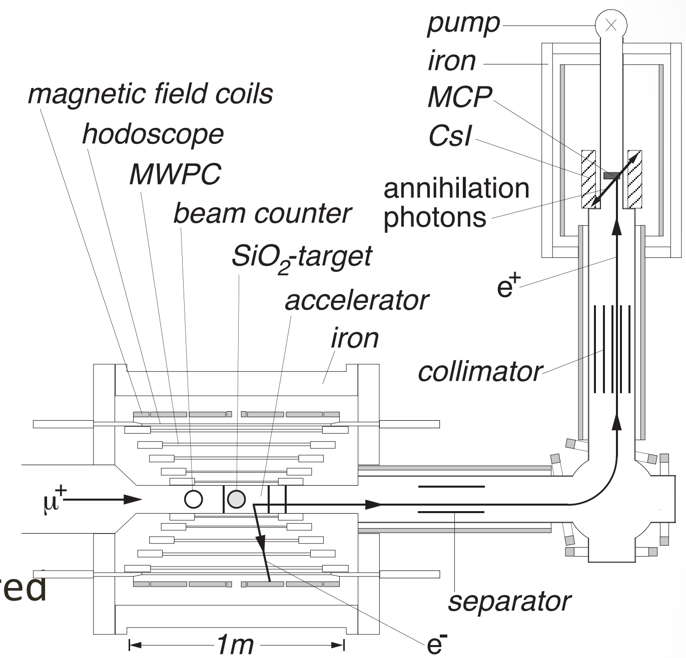
- World's best limit from PSI : (Willmann, L., Jungmann, K. et al. (1999), Phys. Rev. Lett. 82, 49)

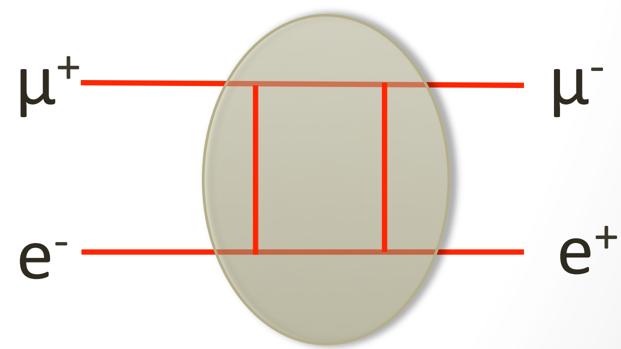
$$\mathrm{G}_{\mathrm{Mu}\overline{\mathrm{Mu}}} < 3 \times 10^{-3}\mathrm{G}_{\mathrm{F}} \ (\text{Probability of spon. transition } < 8.2 \times 10^{-11})$$

- Could be improved x100 with better resolution and pulsed beam, so *~ $10^{-5}G_F$*
  - priv. comm. with Klaus Jungmann

Current Best Muonium

- Stop a μ^+; wait for oscillation; look for muon decay to electron and see the e^+
  - Best experiment could check both muonium and antimuonium, reducing systematics
  - Nice technology in capture of μ^+
    - Entire separate talk
- Limited by timing and resolution
- Backgrounds:
  - Rare $\mu^+ \rightarrow e^+e^-e^-\nu\bar{\nu}$ at 3.4e-05 (same as before!) and see the scattered positron
  - Normal Michel decay positron scatters yielding an electron
- At PX, can wait several muon lifetimes to suppress rare background – using a pulsed beam, not possible at PSI
  - *Another advantage of flexible PX time structure*





Next-Generation *Muon EDM*

$$H = -\vec{\mu} \bullet \vec{B} - \vec{d} \bullet \vec{E} \qquad \vec{\mu}, \vec{d} \parallel \vec{\sigma}$$

	E	B	μ or *d*
P	-	+	+
C	-	-	-
T	+	-	-

$$\vec{d} = \eta \frac{q}{2mc} \vec{s} \qquad \vec{\mu} = g \frac{q}{2m} \vec{s}$$

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2}$$

$$\vec{\omega}_{a\eta} \quad = \quad -\frac{Qe}{m}\left[a_\mu \vec{B} + \left(a_\mu - \left(\frac{m}{p}\right)^2\right)\frac{\vec{\beta} \times \vec{E}}{c}\right] - \eta \frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \beta \times \vec{B}\right]$$

- Assuming CPT, a non-zero *d* implies non-CKM CP violation
  - Huge physics payoff
- Current muon limit ~ 2 x 10^{-19}
- Need a new method ("frozen-spin")
- Choose radial E field to cancel all but η term, and spin will precess -> EDM to 10^{-24} e-cm (see EDM session)

Proton Charge Radius

- Charge Radius of Proton Extracted from Muonic Hydrogen:
  - R. Pohl et al., Nature 466, 213 (2010)
- Radius 5σ from the measurement in regular hydrogen

	r^E_p (fm)	Error
Muonic Lamb Shift	0.84184	0.00067
Electron Lamb Shift	0.8768	0.0069
Electron scattering	0.879	~0.008

- Electrons agree, muons disagree
  - How good is the extraction from scattering measurement? Paz and Hill, http://arxiv.org/pdf/1008.4619.pdf
- New forces? (talk by Hill)
- Low energy muon beams in scattering experiments and/or muonic atoms, both natural territory for PX

Electron Lamb Shift: J. C. Bernauer et al. [A1 Collaboration], Phys. Rev. Lett.105, 242001(2010).

Scattering: P. J. Mohr, B.N. Taylor and D. B. Newell, Rev. Mod.Phys. 80, 633 (2008)

Summary

- Many fascinating problems can be addressed
- With beautiful, elegant measurements
  - *no question that muon physics at PX is important and possible*
- Let's use this Study to start thinking about
  A. What we want to measure
  B. How well we want to measure it
  C. What auxiliary measurements we need to make
  D. What new techniques we need to develop
  E. What infrastructure we need to build
  F. How the program should start and evolve
- With a goal of writing it down for Snowmass